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Sequence Stratigraphic Interpretation of the Olu Oilfield Sediments, Offshore Niger Delta, Nigeria

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Abstract

This paper presents the result of a sequence stratigraphic study on 'Olu' oilfield sediments in the Niger Delta. This study attempts to improve the sequence stratigraphic model of the region using wireline logs and biostratigraphic data. This study will help further to determine geologic ages of the deposits for proper optimization and development of hydrocarbon reservoirs within the oilfield. The stratigraphic analysis of the oilfield was carried out by interpreting the biostratigraphic data utilizing the faunal contents of sediments. From the stratigraphic analysis of the field, two key surfaces were identified; the maximum flooding surfaces and the sequence boundaries. These surfaces were named and dated using the Shell Petroleum Development Company chronostratigraphic chart. The biofacies analysis of the wells further helped in the establishment of the depositional environments. The application of sequence stratigraphy in this study helped to pinpoint potential hydrocarbon reservoirs of interest with good sand geometries. It has also showed that the reservoirs within this field have high potential and they occur mostly in the channel environment deposited within the highstand systems tract. The shale found within the transgressive systems tract of the field also acts as a good seal within the field.

Keywords: Sequence stratigraphy, Systems tracts, Environments of deposition, Biofacies, Niger Delta.

Introduction

Sequence stratigraphic analysis is a valuable tool for understanding and estimating the risk of plays in a particular geologic setting. This gives the oil and gas industries a very competitive advantage and substantially reduce their risk in bidding for offshore blocks by allowing them to properly evaluate new and previously-leased blocks (Vail and Wornardt, 1990).

Sequence stratigraphy is the study of genetically related facies within a framework of chronostratigraphically significant surfaces (Posamentier, et al., 1988). Therefore, this study attempts to subdivide and link sedimentary deposits

into unconformity bound units on a variety of scales and explain their stratigraphic units in terms of variations in sediment supply and variations in the rate of change in accommodation space often associated with changes in relative sea level. The essence of the method is to help us to map a given strata based on the identification of the key surfaces which are assumed to represent time lines, for example, subaerial unconformities, maximum flooding surfaces, and therefore placing stratigraphy in chronostratigraphic framework (Samuel et al., 2011). This however provides a tool used in the interpretation of the depositional origin and prediction of the heterogeneity, extent and character of the sediments deposited in any give environment (Kearey, 2001). Hydrocarbon always occur in stratified sedimentary rocks, therefore the process of locating petroleum reservoir traps has been facilitated significantly by the use of stratigraphic concepts (Anthony and Arelius, 2013 and Edigbue, 2014). Sequence stratigraphic analysis of a reservoir then provides a logical and useful aid in exploration ranging from frontier areas with limited well control to exploration in mature areas with many wells and also show relevance in the production application (Mitchum et al., 1990 and Udoh, 2016).

Sequence stratigraphy is used to locate stratigraphic prospects and to predict reservoir and seal quality on structural prospects. Mature exploration areas allow us to use sequence stratigraphic concepts to recognize detail stratigraphic trap prospects in areas where the potential for larger structural traps is largely exhausted (Adegoke et al., 2012, and Udoh, 2014). The key to using sequence stratigraphic tool for interpreting the sedimentary sections are the utilization of the major bounding surfaces (Fig. 1).

Mapping the right reservoir, determining the thickness and area extent of the reservoir, having a good understanding on how the sediments are being deposited and the geologic ages of the sand bearing hydrocarbon have been a major challenge in the exploration and exploitation of hydrocarbon in major hydrocarbon fields including Niger Delta. Amadi et al., (2015) reported that reservoir characterization using seismic data and well log data alone is not sufficient enough to predict the hydrocarbon reserves within the reservoir and predict the future performance of the reservoir. However, steady success in the exploitation for oil and gas reserves in Niger Delta therefore depend on having a clear understanding of the subsurface geology of the area, detailed knowledge on the environments of deposition of the lithologic units and the ability to accurately predict the petrophysical parameters within the setting (Beka et al., 2016 and Amigun et al., 2012). Identification of the fluid present within the reservoir and the accurate estimation of the amount of reserves in the reservoir horizons will aid in a successful exploitation for hydrocarbons. A successful attempt on reservoir characterization therefore involves the integration of biostratigraphic/biofacies and wireline log datasets. This helps to have a proper understanding on the geology of the area, how the sediments were deposited and the age the sediments deposited. This study therefore focus on the integration of wireline well logs and biofacies datasets in other to have a proper understanding on how the sediments were deposited within this field and also to determine their geologic ages for proper optimization and development of hydrocarbon potential within the field. The combined application of both biofacies and well log motifs data also help to properly delineate the stratigraphic sequences within the field that have potentials to serve as excellent source rock and seals.

Location the study and geology of the Niger Delta

The ‘Olu’ oilfield is an offshore field located in Rivers State, Nigeria. It is located between latitude 4°33’1”N and 4°33’20”N and longitude 6°53’45”E

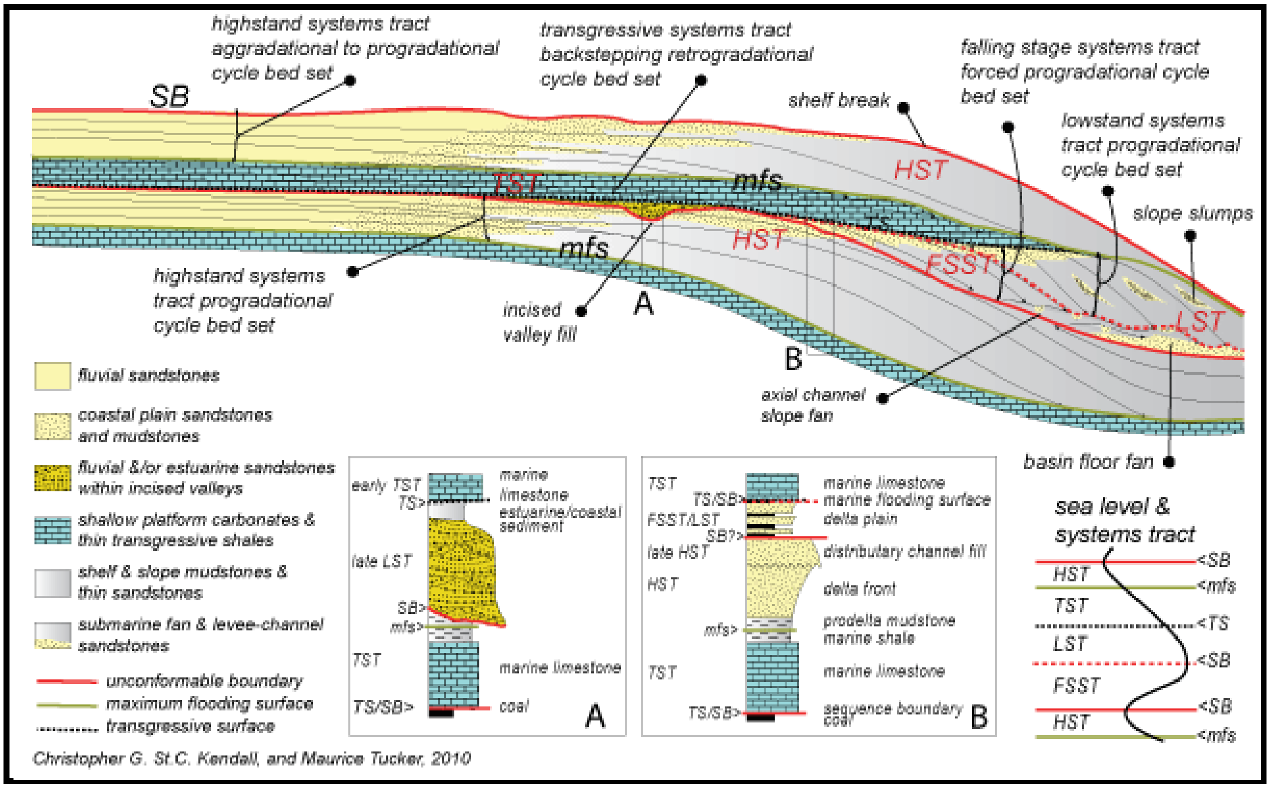

Fig.1. Sequence Stratigraphic Deposition model (After Mitchum et al., 1990).

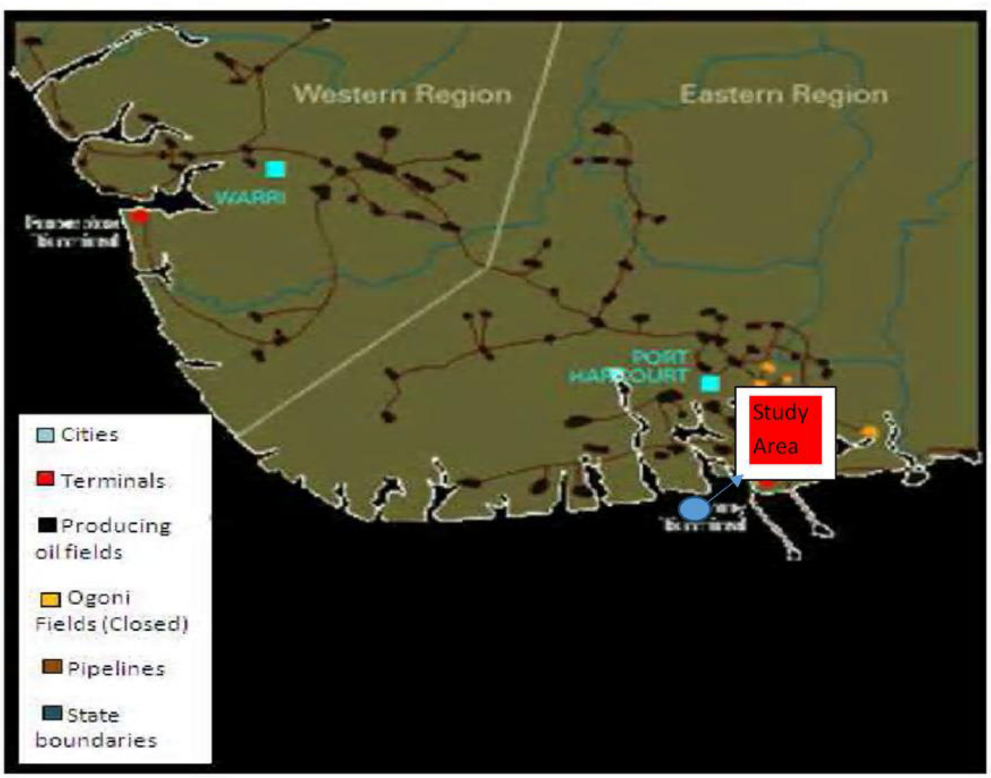

Fig. 2. Location map of the Niger Delta showing 'Olu' Field (Modified from Imasuen et al., 2011).

and 6°54'7"E (Fig. 2). The base map for the survey area is shown in the figure below (Fig. 3).

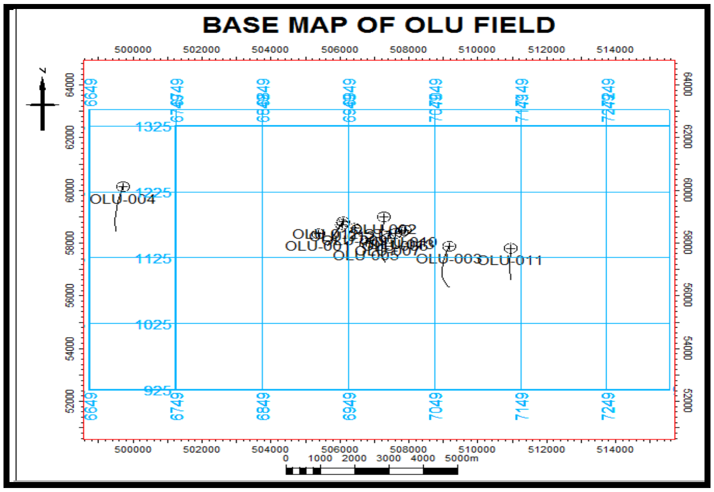

Fig. 3. Base map of 'OLU' field showing the well locations.

The Niger Delta is a prolific hydrocarbon belt in the world. The formation of Niger Delta basin was initiated in the early Tertiary time (Ekweozor and Daukoru, 1984; Bustin, 1988). The Niger Delta is situated in the Gulf of Guinea and extends throughout the Niger Delta province. It has been recorded that from the Eocene to the present, the delta has prograded Southwest ward, forming depobelts that represent the most active portion of the delta at each stage of its development. Deposition of the three formations (Benin, Agbada and Akata) occurred in each of the five off lapping siliciclastic sedimentation cycles (Fig. 4) that comprise the Niger Delta (Weber and Daukoru, 1988 and Weber, 1987). These cycles are 30 - 60 kilometers wide, prograde southwestward 250 kilometers over oceanic coast into the Gulf of Guinea, and are defined by syn-sedimentary faulting that occurred in response to variable rates of subsidence and sediment supply (Stacher, 1995).

Deposition of the overlying Agbada Formation, the major petroleum-bearing unit, began in the Eocene and continues into the Recent. The formation consists of paralic siliciclastics over 3700 meters thick and represents the actual deltaic portion of the sequence. These clastics accumulated in the delta-front, delta-topset, and fluvio-deltaic environments (Short and Stauble, 1967). In the lower Agbada Formation, shale and sandstone beds were deposited in equal proportions, however, the upper portion is mostly sand with only minor shale interbeds. The Agbada Formation is overlain by the third formation, the Benin Formation, a continental latest Eocene to Recent deposit of alluvial and upper coastal plain sands that are up to 2000 m thick (Avbovbo, 1978). In the Niger Delta province, the Tertiary Niger Delta petroleum system described as Akata-Agbada has been identified (Ekweozorand Okoye, 1980; Nwachukwu and Chukwura, 1986).

The delta formed at the site of a rift triple junction related to the opening of the Southern Atlantic starting in the Late Jurassic from interbedded marine shale of the lowermost Agbada Formation and continuing into the Cretaceous. The delta properly began developing in the Eocene, accumulating sediments that now are over 10km thick. The primary source rock is the upper Akata Formation, the marine shale facies of the delta, with possibly contribution from interbedded marine shale of the lowermost Agbada Formation. Oil is produced from the sandstone facies found within the Agbada Formation, however, turbidite sand in the upper Akata Formation is a potential target in deep water offshore and possibly beneath the currently producing intervals onshore. The intervals, however, rarely reach thickness sufficient to produce a world class oil province and are immature in various parts of the delta (Stacher, 1995). The Akata shale is present in large volumes beneath the Agbada Formation and is at least volumetrically sufficient to generate enough oil. Based on organic-matter content and its types, Evamy et al., (1978) proposed that both the marine shale (Akata Formation.) and the shale interbedded with paralic sandstone (lower Agbada Formation)

were the source rocks for the Niger Delta oils (Michele et al., 1999).

Petroleum occurs throughout the Agbada Formation of the Niger Delta, however, several directional trends form an "oil-rich belt" having the largest field and lowest gas: oil ratio (Ejedawe, 1981 and Doust and Omatsola, 1990). The belt extends from the northwest offshore area to the southeast offshore and along a number of north-south trends in the area of Port Harcourt. It roughly corresponds to the transition between the Continental and Oceanic crust, and is within the axis of maximum sedimentary thickness. This hydrocarbon distribution was originally attributed to the timing of trap formation relative to petroleum migration (earlier landward structures trapped earlier migrating oil). Evamy et al., (1978), however, showed that in many rollovers, movement on the structure building fault and resulting growth continued and was relayed progressively southward into the younger part of the section by successive crestal faults. He also concluded that there was no relation between growth along a fault and distribution of petroleum. Ejedawe, (1981) however, relates the position of the oil-rich areas within the belt to five delta lobes fed by four different rivers.

Materials and Method

The materials used in carrying out the analysis for the ‘Olu’ field study include the following: Petrel software, well header, deviation, well logs and biostratigraphic/bio-facies datasets, respectively. All the datasets provided for this study was quality checked before loading them into the Petrel software for the interpretation.

The lithology was delineated by first setting a range for all the gamma ray log motifs and its corresponding resistivity log signatures. The gamma ray logs ranges from 0 to 150API. A cut-off limit of 75 API was used. The shale formations is believed to show high radioactive contents, thus deflect to the right and beyond the baseline while the sand formations will deflect to the left of the baseline since they have low radioactive contents. Two reservoirs were correlated across the eight wells using both the gamma ray and the resistivity log signatures respectively. The fluid type within this reservoirs were identified using both the neutron and density logs as they showed a loop upon crossing each other.The encountered facies within the wells comprises of channels, barrier bars complexes, restricted mudstones and delta-marine fringes. Four basic environments of deposition were identified in the ‘Olu’ oilfield consists of: Channels, Shoreface sands (that is., Lower and Upper shorefaces) and Shales deposits. These depositional settings were identified based on their log signatures which could be smooth/cylindrical, blocky (erosional base), funnel and bell shapes respectively. Channel sands are blocky, cylindrical, serrated and in some cases have fining upward units and their readings ranges from 20– 70[g (API)]. They have conspicuous flat bases. The upper shoreface sands are blocky with reading range of 30 - 60[g (API)]. On the other hand, the lower shoreface sands have a coarsening upward sequence pattern with 45 – 90[g (API)] range readings while the Shales deposits are either marine shales or coastal plain shales that show reading ranges from >100 - 150[g (API).

The stratigraphic analysis of the ‘Olu’ field was carried out based on the information gotten from the bio-facies data which serves as the engine block for this interpretation. The systems tracts identified in this study include highstand systems tract (HST), lowstand systems tract (LST), and transgressive systems tract (TST). The gamma ray and resistivity log motifs were also used to infer the peak of the individual system tract delineated on each of the well section. Two major surfaces were identified utilizing the biofacies data and the log signatures. These surfaces include the Maximum Flooding Surfaces (MFS) and the Sequence

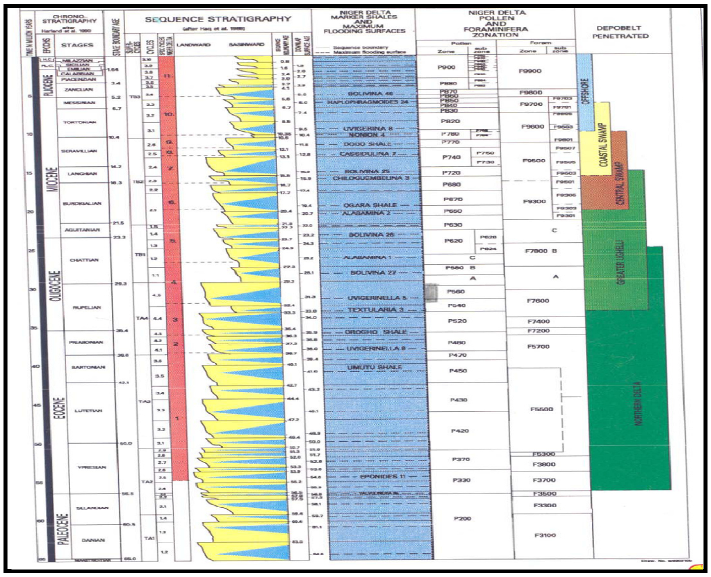

Fig. 4. Niger Delta Chronostratigraphic Chart.

Boundary (SB). All encountered Maximum Flooding Surfaces correspond to increase in abundance of microfauna contents while the sequence boundary depicts relatively low microfauna contents deposition. Inference from the gamma ray log was also used to affirm the stratigraphic surfaces delineated from the biofacies data. However, the Maximum Flooding Surfaces (MFSs) were identified as the highest peak part with a high gamma ray value while the corresponding sequence boundaries are identified within the coarsening upward sequence pattern with low valued gamma ray log motifs. The ages of the key surfaces was then determined by utilizing the biozones information correlated to the Shell Petroleum Development Company Niger Delta chronostratigraphic chart (Fig. 4).

Sequence stratigraphic interpretation was achieved by the integration of biostratigraphic, paleobathymetric and wireline (Gamma ray and Resistivity) log datasets. The approach of Vail and Wornadt, (1991) was adopted; bearing in mind the pitfalls (cave-ins, sampling interval, sample type) commonly associated with facies analysis. The Maximum Flooding Surface (MFS) candidate was delineated based on the high gamma ray log values associated with relatively high abundance and diversity of microfauna. No Sequence Boundary (SB) candidate on the other hand, was delineated due to the short nature of the well interval under study. The dating of these surfaces was achieved by correlation to the third order cycles chart of Haq et al., (1988) in association with chronologically significant bioevents. The highstand systems tract (HST) is bounded by Maximum Flooding Surface (MFS) at the bottom and unconformities at the top. The transgressive systems tract (TST) is bounded by maximum regressive surface (MRS) at the bottom and MFS at the top. The lowstand system tract (LST) is bounded by the unconformities at the base and the MRS at the top.

Results and Discussion

The well correlation of the ‘Olu’ field was carried out along both the strike and dip directions respectively (Figs. 5 and 6). Five wells namely; OLU-010, 0LU-0I3, OLU-006, OLU-007, and OLU-005 were correlated along the strike direction (Fig. 5) while three others wells namely, OLU-009, OLU-012STI and OLU-001 (Fig. 6) were also correlated along the dip direction respectively. One of the major reasons of carrying out correlation exercise within the given wells section is to have an idea of the occurrences of horizontal sand packages from one well to the other and possibly deposited at the same time and space within the field. It was further observed from the correlation panel that the sand packages are thinning towards the N-E direction. However, correlation along the dip direction, did not indicate much displacement within the sand horizons. Six reservoirs zones were identified within this field. They include:

1. Reservoir K_2000,
2. Reservoir M_4000,
3. Reservoir O_6000,
4. Reservoir Q_8000,
5. Reservoir R_9000 and
6. Reservoir S_10000.

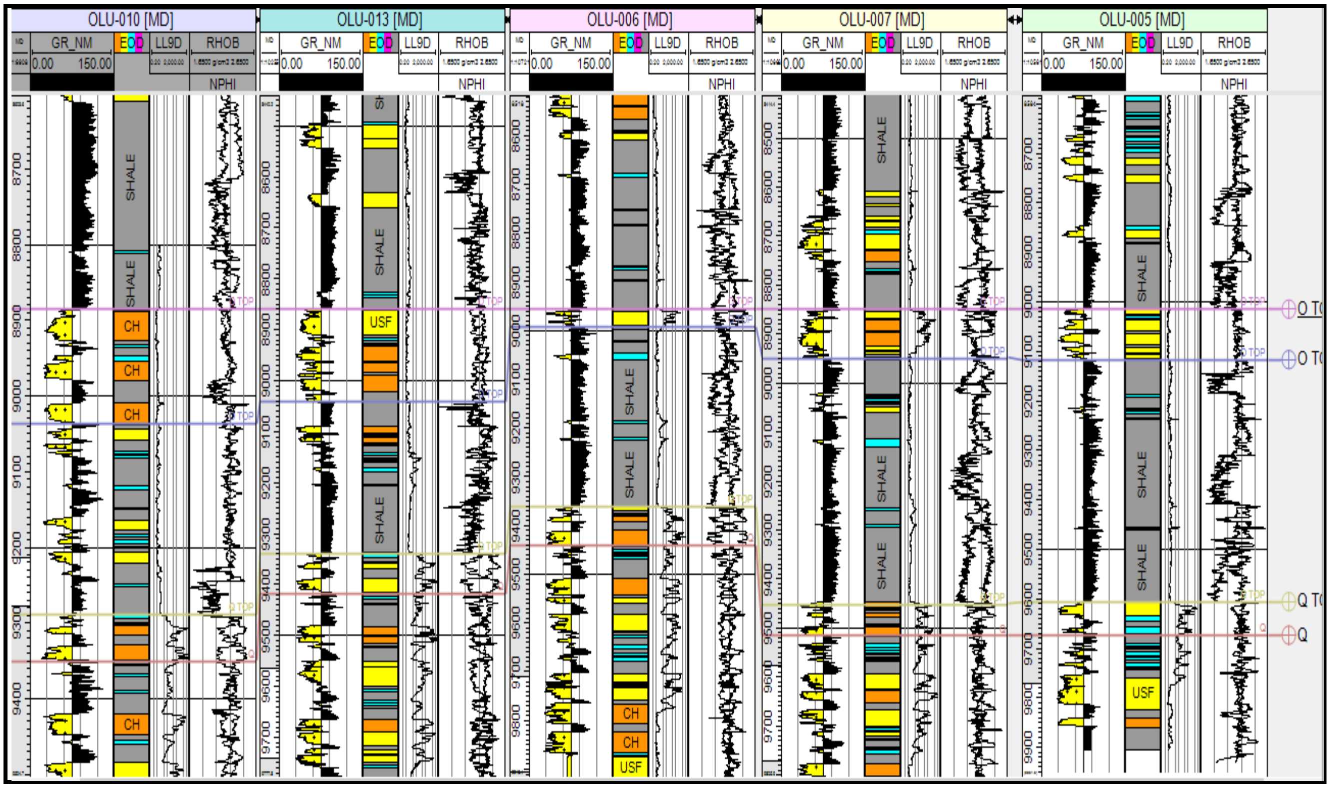

Fig.5. Lithology Delineation and Reservoir Identification along the Strike.

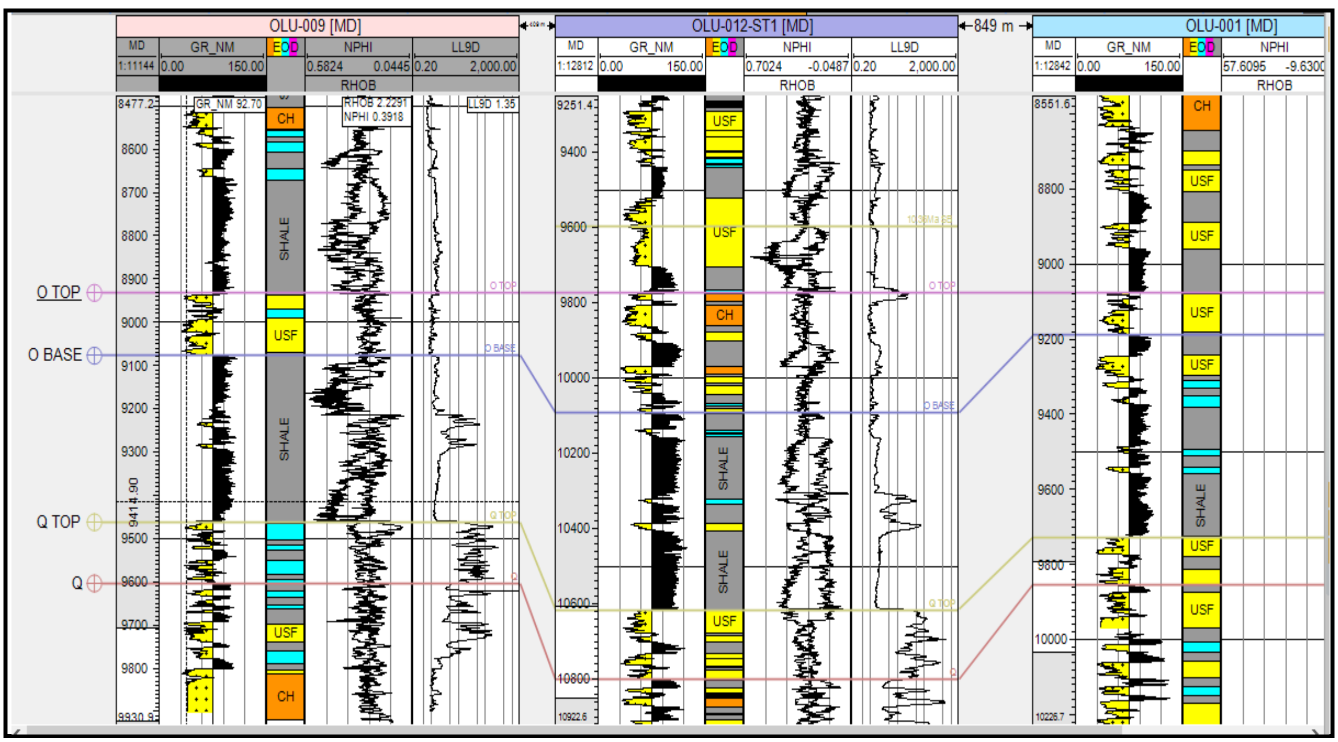

Fig.6. Lithology delineation and reservoir identification along the strike setion.

The fluid types (oil and gas) within these reservoirs were identified using both the neutron log and density log respectively. It was observed that most of the reservoirs found within the wells in this field were completely saturated with gas.

Stratigraphic Sequences and Systems Tracts Delineations

The first Maximum Flooding Surface designated as MFS1 was delineated in well OLU-002 at 14860ft (Fig. 7) and was dated 11.5/Ser.3Ma using the Niger Delta Chronostratigraphic Chart, it is characterized by a shale marker called DODO SHALE and the occurrence of the event is within P770 and F9500 paly/biozones.

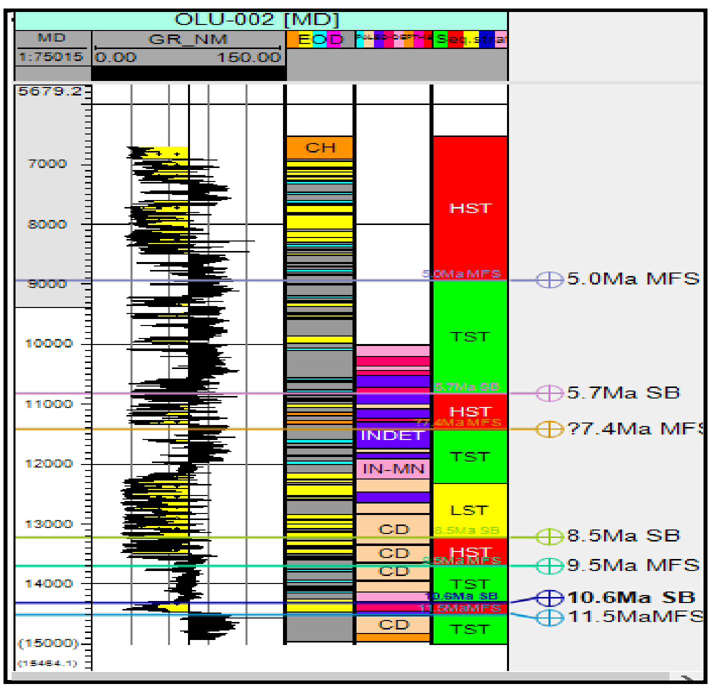

Fig.7. Sequence stratigraphic setting of OLU-002 sediments.

The Maximum Flooding Surface (MFS1) recognized in OLU-012 well at 9740ft was correlated to MFS2 of OLU-002 at 14290ft, and is dated 10.4Ma. The surface occurred within P780 and F9600 biozone and is characterized by *Florilusex.gr. costiferum* Shale marker. MFS2 in OLU-012 at 8180ft, correlates with MFS3 of OLU-002 at 11920ft and is dated 9.5/Tor.1Ma. This MFS occurred within P780 and F9600 zone and is characterized by *Uvigerina superegrina* shale marker. The MFS3 identified in OLU-012 well at 6380ft correlated with the MFS4 identified in OLU-002 well at 11270ft and is dated 7.4/Tor.2Ma. This 7.4/Tor.2MFS is characterized by unnamed shale marker and is defined within the P780 and F9600 biozones. The MSF5 identified in OLU-002 well at 10450ft is dated 5.0/Me.1Ma. However, this MFS is characterized by *Haplophragmoides narivaensis* shale marker. The biozones was not studied in the analyzed well. The summary of all the identified MFSs and their occurring depths are shown in Tables 1-3.

Conversely, sequence boundaries (SB) were also delineated in the study wells. The oldest Sequence Boundary (SB1) identified at 14530ft in the field is dated 10.6Ma. The surface represents a substantial erosional surface defined before the 9.5/Tor.2MaMFS (Figs. 8 and 9). SB1 is overlain in the down dip section by a relatively thick and sharp-based sand unit identified as incised valley fills and in the up dip area by sharp-top facies of the upper most prograding high stand parasequence. SB2, SB3, and SB4 are dated 10.36Ma, 8.5Ma, and 5.7Ma respectively, based on their relative positions in the stratigraphic sections and correlated to the Niger Delta chronostratigraphic chart.

Five depositional sequences (SEQC1, SEQC2, SEQC3, SEQC4 and SEQC5) and the accompanying systems tracts were interpreted and mapped in the 'Olu' Field, based on the biostratigraphy data derived from OLU-002 and OLU-012 and the spatial distribution of the delineated key surfaces (MFSs and SBs).

The SEQC1 and SEQC5 sequences were formed in the deepest (oldest) and the shallowest (youngest) depositional sequences respectively. SEQC1 which is

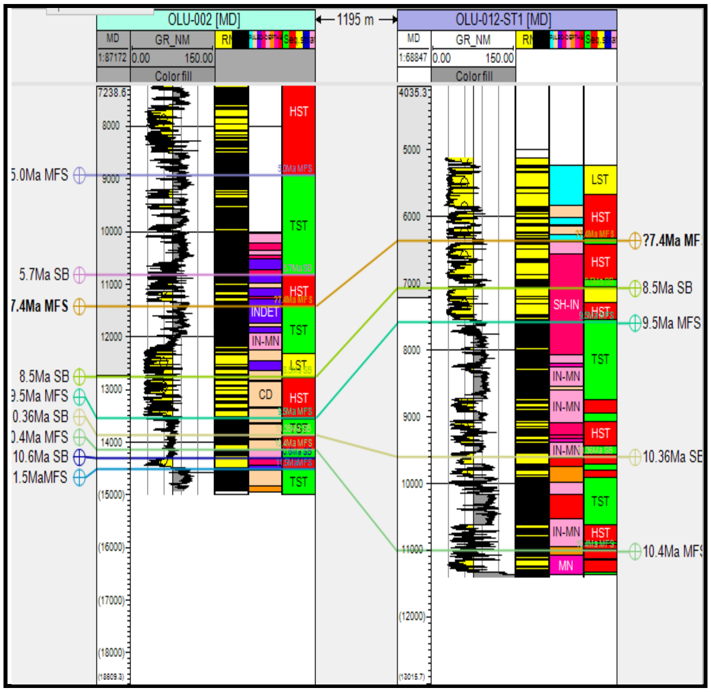

Fig. 8. Depositional Sequences Identified Within 'Olu' Field.

only found OLU-002 is about 86ft thick. It is accompanied by a Transgressive systems tract (TST) containing marine shales rich in microfauna contents and are enveloped by the 11.5/Ser.3MaMFS. This predominantly shales litho-units encountered within this interval are associated with finning and minor coarsening upwards of the sediments. This is an indicative of a transgressive episode and is characterized by stacks of retrogradational log motifs. It was deposited in the Middle Neritic paleo water depth. The Highstand Systems Tract (HST) of the sequence, was estimated to be about 330ft thick. It was deposited within the Inner - Middle Neritic setting depicting mainly progradational/aggradational stacking patterns.

SEQC2 was delineated in both OLU-002 and OLU-012. It has an approximate thickness of about 2040ft and 1633ft respectively. The Highstand systems tract (HST) in OLU-002 was deposited in the Inner Neritic – Shallow Inner paleo water depth and was also deposited within in the Middle-Outer Neritic through Shallow – Inner Neritic in OLU-012. The Highstand systems tract in OLU-002 was observed to be barren of microfauna contents and underlies the Transgressive systems tract about 240ft thick. However, the shale with minor sands/sandstones lithofacies encountered within this highstand system tract were deposited in an overall shallowing upward depositional medium.

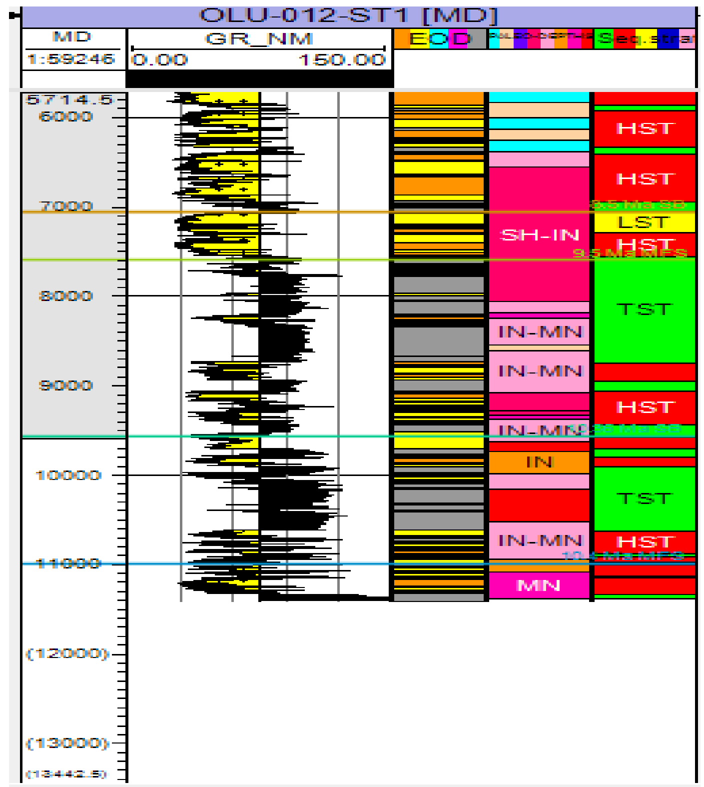

Fig. 9. Sequence Stratigraphic Setting of OLU-012 sediments.

SEQC3 overlies the 10.36MaSB and is accompanied by the 8.5MaSB. The sequence was identified at the depth ranging from 11470 -1250ft in OLU-001and from a depth range of 6380 - 8180ft in OLU-012 well respectively. This sequence displayed predominant fluvial and tidal processes (progradational) while the encountered Lowstand systems tract of this sequence contains channelized sand deposits which are more pronounced in the down dip wells.

SEQC4 is the fourth sequence identified in the study area. It unveiled on the 8.5MaSB and is capped by the

Table 1. Stratigraphic analysis of Olu-002 well based on biostratigraphic data.

Dept(ft).	Systems tracts & Key Surfaces	F- Zone	Age
10450-10000	HST	Not Studied	Late Miocene
10450	MFS5 (?5.0Ma)		
10870-10450	TST	F-9600	
10870	SB4 (?5.7 Ma)		
11270-10870	HST		
11270	MFS4 (?7.4Ma)		
11270 -11370	TST		
11370 - 11470	LST		
11470	SB3 (8.5 Ma)		
11920-11470	HST		
11920	MFS3 (9.5 Ma)		
12250-11920	TST		
12250	SB2 (10.36 Ma)		
14290-12250	HST		
14290	MFS2 (10.4 Ma)		
14530-14290	TST		
14530	SB1 (10.6 Ma)		
14860-14530	HST		
14860	MFS1 (11.5 Ma)	F-9500	
14860-14916	TST		

Table 2. Stratigraphic analysis of Olu-012ST well based on biostratigraphic data.

Depth (ft)	Systems tracts&Key Surfaces	F-Zone	Age
5000-5230	LST	F-9600	Late Miocene
6230-5350	HST		
6350	MFS3 (7.4 Ma)		
7410-6350	TST		
7580 -6410	LST		
7580	SB2 (8.5 Ma)		
8180-7580	HST		
8180	MFS2 (9.5 Ma)		
8720-8180	TST		
8720	SB1 (10.36 Ma)		
9740-8720	HST		
9740	MFS1 (10.4 Ma)		
11373-9740	TST		

Table 3. Delineated MFS, Marker Shales and Biozones from Olu-002 and 0012 Wells.

<table>
<tr><th>Chronostratigraphic Surfaces</th><th>Dated age (Ma)</th><th>Shale markers</th><th colspan="2">Biozones (P & F- Zones)</th><th colspan="2">Depth (ft).
OLU-002 & OLU-012</th></tr>
<tr><td>MFS5</td><td>?5.0</td><td>Haplophragmoides narivaensis</td><td colspan="2">Not Studied</td><td>10450</td><td>-</td></tr>
<tr><td>MFS4</td><td>?7.4</td><td>Unnamed</td><td>P780</td><td rowspan="3">F9600</td><td>11270</td><td>6380</td></tr>
<tr><td>MFS3</td><td>9.5</td><td>Florilusex.gr. costiferum</td><td rowspan="2">P780</td><td>11920</td><td>8180</td></tr>
<tr><td>MFS2</td><td>10.4</td><td>Uvigerina superegrina</td><td>14920</td><td>9740</td></tr>
<tr><td>MFS1</td><td>11.5</td><td>DODO SHALE</td><td>P770</td><td>F9500</td><td>14860</td><td>-</td></tr>
</table>

5.7MaSB. It has a thickness of about 600ft in OLU-001 and a thickness of about 1160ft in well OLU-012. The Highstand system tract in OLU-012 is deposited within the Inner Middle - Shallow Inner Neritic paleo water depth. Conversely, the transgressive systems tract was deposited within the Middle to Inner through Middle Neritic bathymetric depth. However, the Transgressive system tract in OLU-002 was deposited within the Shallow–Inner – Inner through Middle Neritic paleo-depositional environment while the Highstand systems tract was also deposited in a predominantly shallow-inner neritic paleo-depositional environment.

SEQC5 is the youngest depositional sequence identified within ‘Olu’ Field. It was only identified in OLU-002 well. It is the shallowest sequence depositional sequence within ‘Olu’ field. However, this sequence consists of thick sand units at its base with a gradual decrease in the gamma log value. The sequence was deposited within the Inner-Neritic paleo depositional environment which also shows the 5.0MaMFS within this sequence.

Reservoir potential of the ‘Olu’ Field

The six potential reservoirs (Reservoir K_2000, Reservoir M_4000, Reservoir O_6000, Reservoir Q_8000, Reservoir R_9000, and Reservoir S_10000) delineated in the ‘Olu’ Field were mainly channel sands and upper shoreface sands of occurring within the Highstand systems tracts. They displayed low gamma ray and high resistivity values (Fig 10).

Trapping mechanism of ‘Olu’ Field

The most common trapping mechanism found within the Niger Delta environment is the structural traps such as the normal fault, growth fault, roll-over anticline, synthetic and antithetic faults. Also, the stratigraphic trapping mechanism can be found within some depositional environment within the flank of Niger Delta basin which on the other hand also has important structural trapping mechanism. The primary seal rock in the Niger Delta is the interbedded shale within the Agbada Formation. This study has shown that the field is somewhat faulted and these marker shales now serve as the main trapping mechanism for hydrocarbon within the field.

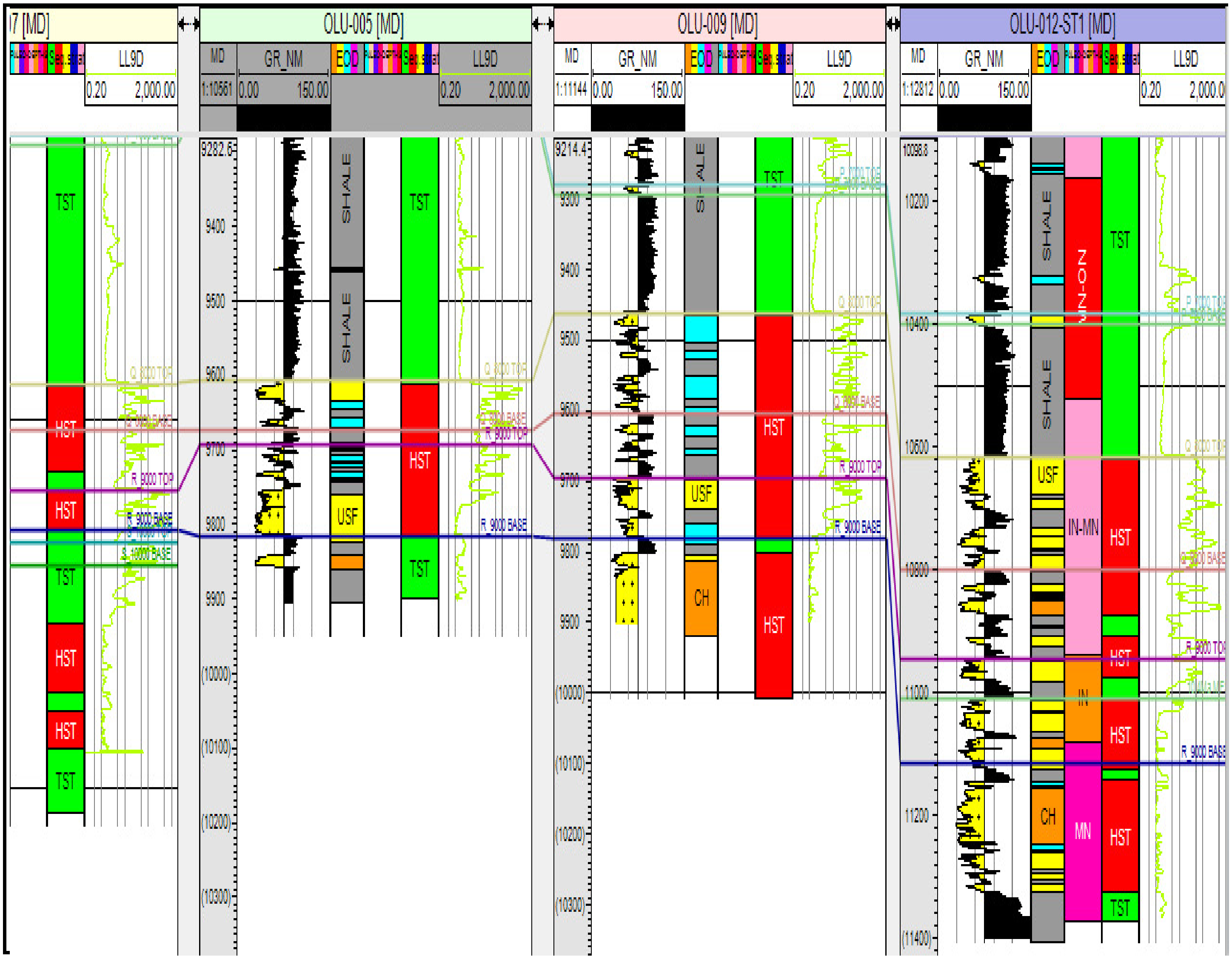

Fig.10. Reservoirs delineated within the depositional Sequence identified of 'Olu Field.

Also, the reservoirs found within the highstand systems tracts (HST) are found between two impermeable beds, that is, the shale. The shale sediment of transgressive systems tracts (TST) were found to be very continuous within the field and could form top and bottom seals for hydrocarbons in the reservoir sands. The reservoir rocks of the highstand systems tracts (HST) and the seals from pro-delta shales of the transgressive systems tract (TST) can combine to constitute stratigraphic traps for hydrocarbon accumulation in the field.

Conclusion

The clastic sedimentary successions in Olu field were analysed using sequence stratigraphic principles that involve the use of parasequence sets stacking pattern to interpret systems tracts sequences and depositional environments. This study showed the versatility of integrating biostratigraphic/biofacies and well log datasets for optimization and development of hydrocarbon potential in 'Olu' field adopting the sequence stratigraphic approach. Series of forestepping and basinward progradational coarsening

upward sequences were interpreted as well as successions of backstepping, landward and retrogradational fining upward units which resulted in the establishment of the respective systems tracts. The stratigraphic analysis of the field has helped to establish that these wells are characteristic of an alternating highstand, lowstand, transgressive and lowstand system tracts respectively. It has also helped to establish that the reservoirs zones within this field are highly potential since the hydrocarbon bearing sands interpreted from wireline logs were found to be laterally continuous and occur mostly within the channels and upper shorefaces depositional environment encountered within the highstand systems tract. The shale found within the transgressive systems tract within the wells in this field can serve as a seal.

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